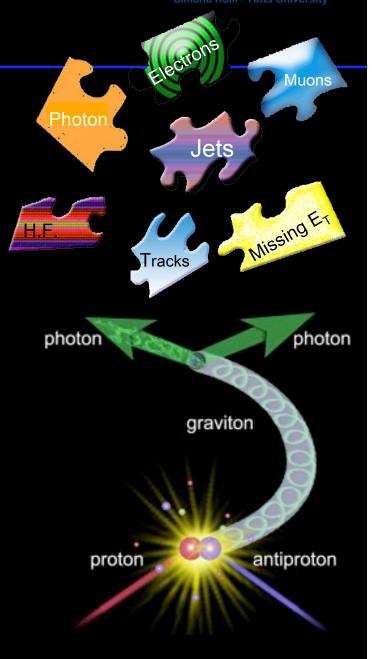
CIPANP 2009: Tenth Conference on the Intersections of Particle and Nuclear Physics

Torrey Pines Hilton—San Diego, California—26 May to 31 May, 2009



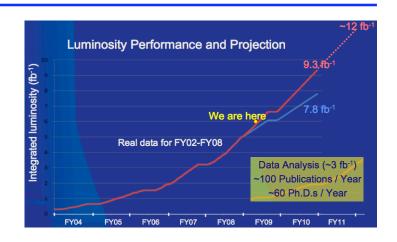
Outline of the talk

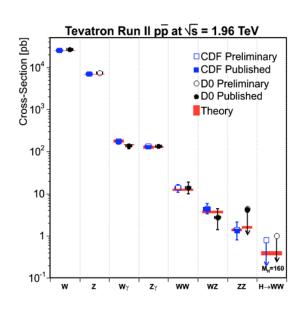
- TeVatron status
- Signature-based searches
 - from simple objects to complex final states
 - leptons-only final states (and isolated tracks)
 - ... + Missing Energy and Photons
 - ... + Jets and heavy flavors
 - Search for SUSY
- Final remarks and conclusions



Tevatron Status

- The TeVatron is currently the highest energy running collider in the world
 - ppbar collider, located about 30 miles west of Chicago, IL
 - 1.96 TeV in the C.M.
 - Data are accumulated at fast rate continuously
 - The machine and the detectors (CDF and D0) are performing very well
 - systematic uncertainties are very well under control
 - Measurements are becoming very precise
 - Top quark mass known with precision < 2%
 - New analyses are now looking for the needle in the hay stack
 - low cross section phenomena







Signatures and Physics Objects

Many processes: several signatures

Leptons-only final states

- e/μ identification well understood
- \bullet τ id a little more complex
- Straightforward and highly efficient approach to search for anomalies

+ Missing Energy and Photons

- Wealth of models and exotic processes
- Need accurate understanding of detector effects
- •... + Jets and heavy flavors
 - More complex signatures
 - Maintaining high S/√B

When a <u>signature-based</u> approach is advocated, final results are generally interpreted in terms of specific models (typical case dilepton searches, MET + jets)

When the analysis is <u>model driven</u> and results are presented as testing of a specific model, there is always a check on control regions, defined in terms of the process signature (blind analyses)

The two approaches are usually pursued in a balanced and complementary way



Signature-based searches

Simona Rolli - Tufts University

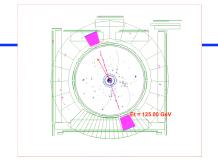
Open searches, final states are analyzed for anomalies when compared with the SM

- Mass bumps searches
- Multi-objects final state (low background)
- Global Searches

Identification efficiency, detector effects and systematic uncertainties need to be very well understood.

The analysis might not be optimized for the latest theory model available but it might be general enough to exclude several other models.

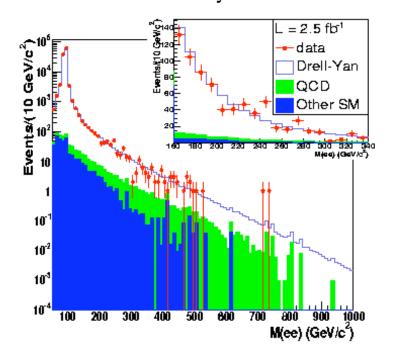
Dilepton final states

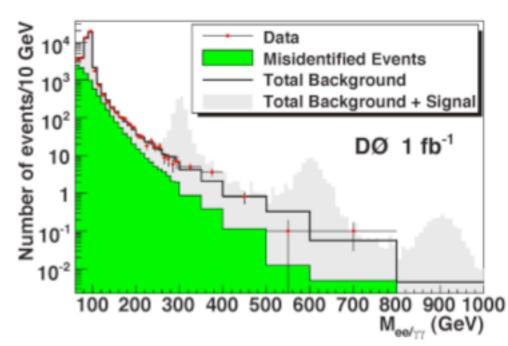


Old-fashioned mass bump hunt...

CDF (X \rightarrow ee)—excess at ~240 GeV (p=0.6% for 0.15-1 TeV) DØ (X \rightarrow ee/ $\gamma\gamma$)—no significant excess at any mass

CDF Run II Preliminary



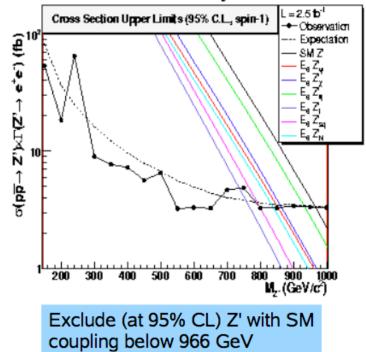


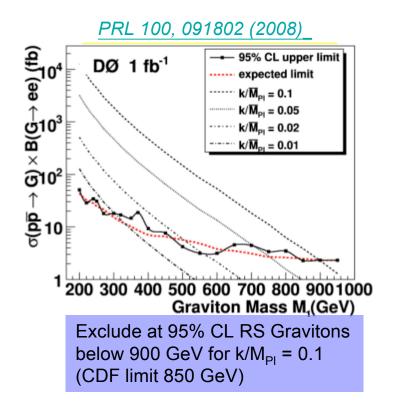
Testing different models

Once the data spectrum is well understood in terms of SM background, from MC, the acceptances for resonant states for different spin particles are derived (Z', RS Graviton) and the expected number of BSM events is calculated.

In the absence of an excess of data, 95% CL limits on production cross-sections and mass of the particles are set.

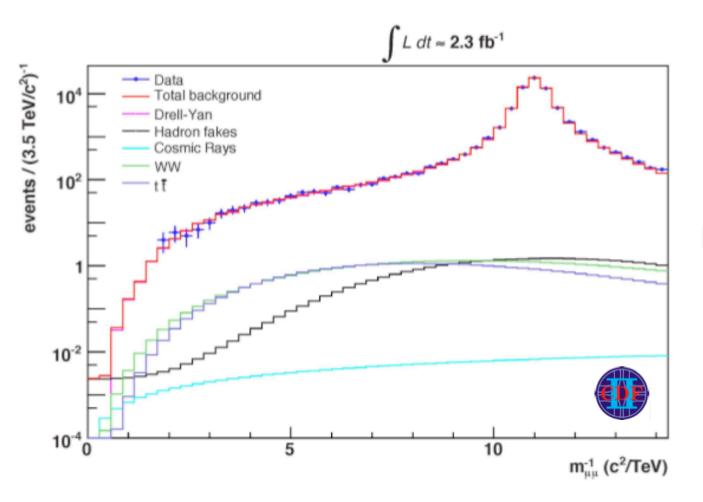
CDF Run II Preliminary





Z' searches

CDF looks for bump in the $X\rightarrow \mu\mu$ final state

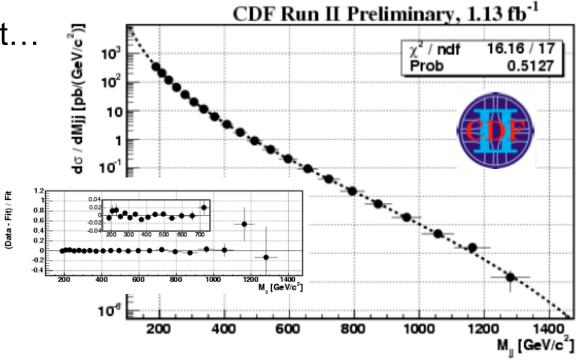


No excess

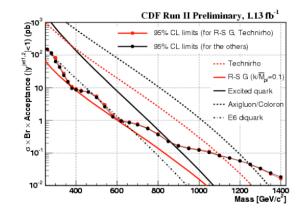
Dijets final state

Another mass bump hunt...

- Choose events with two highp_⊤ jets with rapidity less than
 1.0. Look for an excess in the dijet mass spectrum for masses above 180 GeV
- Possible signals include excited quarks, W', Z', and Randall-Sundrum gravitons
- Find functional form of dijet spectrum in pythia and herwig, fit to data. Look for "bumps" in the data minus fit plot



- No significant resonant structure is observed, so limits are set on various models
- Excludes (at 95% CL) excited quarks from 260-870 GeV, W' from 280-840 GeV, and Z' from 320-740 GeV



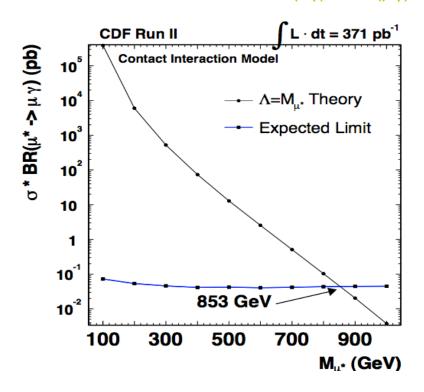
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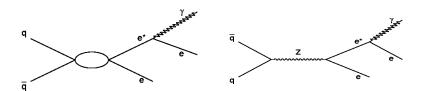
Lepton+γ final states: Excited leptons

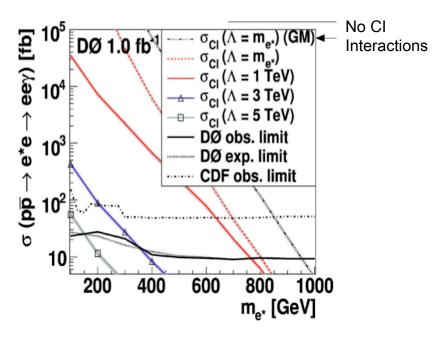
Observation of excited states of quarks and leptons might confirm the hypothesis that they are not elementary particles, but composite states

Select events with eey $(\mu\mu\gamma)$ in the final state and look for resonance in $M(e\gamma)$ or $M(\mu\gamma)$



At Tevatron, e^*/μ^* can be produced via contact interactions or gauge mediated interactions



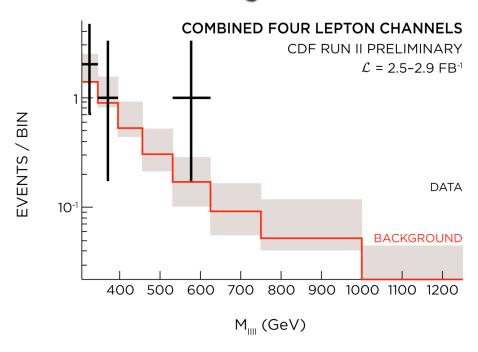


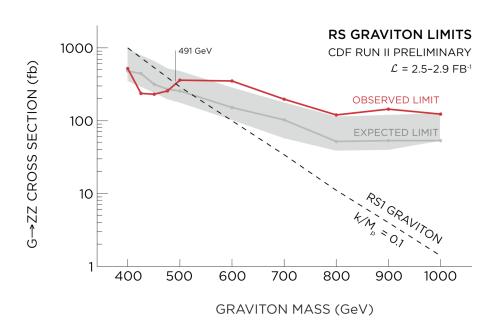
Diboson resonance searches: ZZ



CDF ($X \rightarrow ZZ \rightarrow IIII,IIjj; I=e,\mu$):

newly-improved forward track reconstruction more efficient muon identification no significant excess





RS (spin 2) G→ZZ

 $M>491 \text{ GeV} (2.5-2.9 \text{ fb}^{-1}, \text{ k/M}_{p}=0.1)$

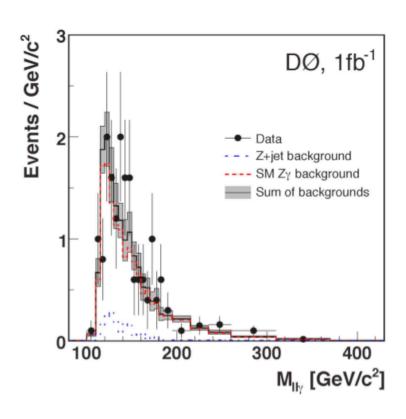
Diboson resonance searches: Z_Y

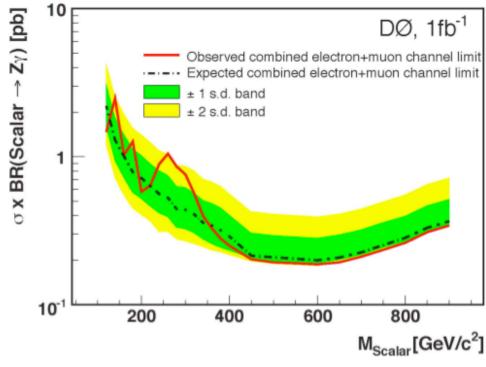


DØ (X \rightarrow Z γ \rightarrow ee/ $\mu\mu$ γ): no significant excess

Scalar [Vector] X

$$\sigma \cdot Br(X \rightarrow Z\gamma) < 0.19[0.20] \text{ pb } (M_X = 600 \text{ GeV})$$
 < 2.5[3.1] pb $(M_X = 140 \text{ GeV})$





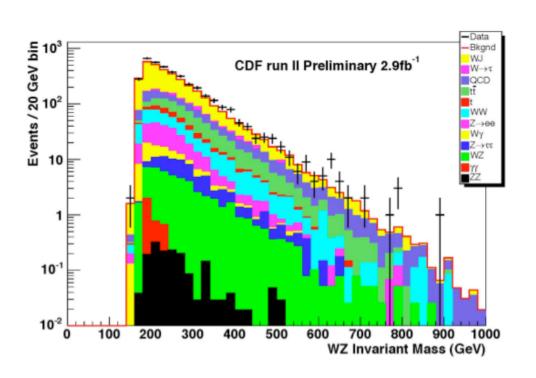
Diboson resonance searches: WW/WZ

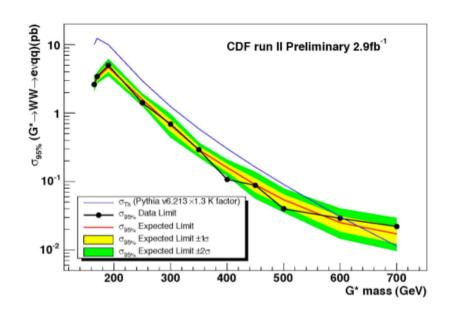
Simona Rolli - Tufts University



CDF (X→WW/WZ→evjj): no significant excess ⇒ set limits on W', Z', RS graviton

$$M_{w'} \notin (284,515) \text{ GeV}$$
 $M_{z'} \notin (247,545) \text{ GeV}$ $M_{g} > 607 \text{ GeV} (k/M_{p} = 0.1)$

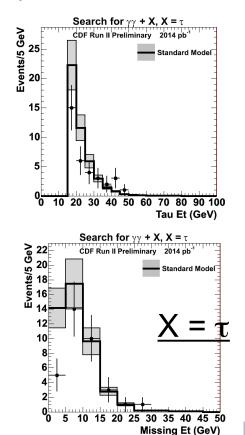




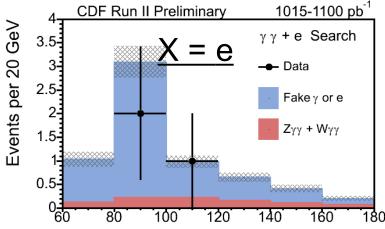
Diphoton+X

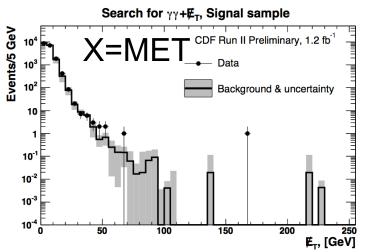
Nominal high E_T object identification and kinematic selections are used.

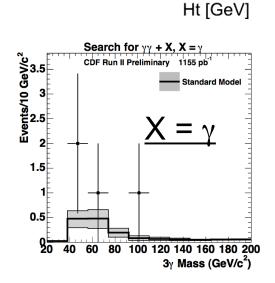
The observed event counts is reported as well as SM prediction for various kinematic distributions





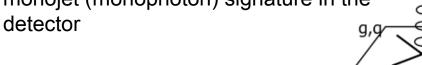


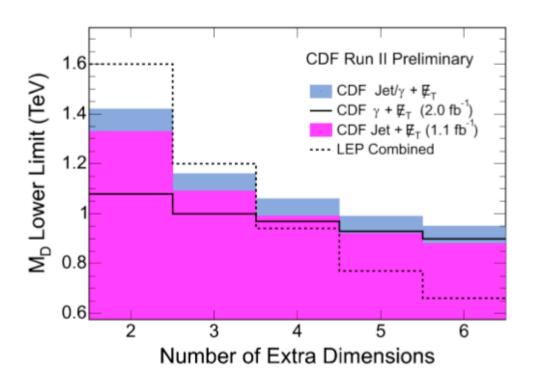


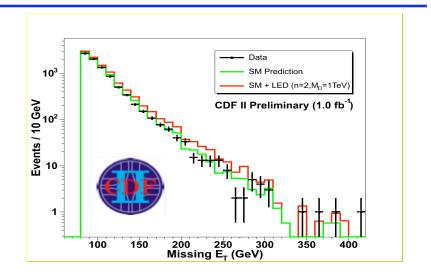


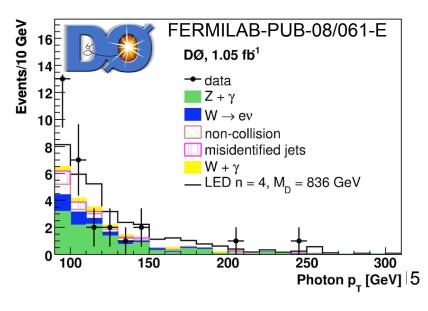
Single jet + MET: LED

A Kaluza-Klein graviton is produced in association with a jet (or photon). The graviton escapes detection, leaving a monojet (monophoton) signature in the

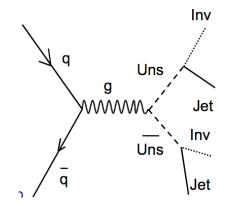








Jets+MET final state:Leptoquarks



The analysis is a counting experiment examining two different kinematic regions (each region being more sensitive to different models).

Cuts are not optimized for a specific model.

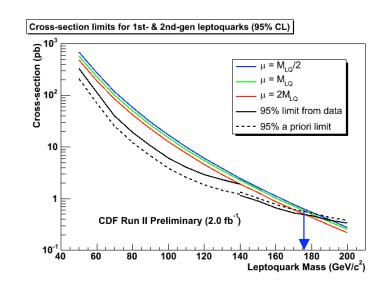
Main backgrounds:

- $-Z \rightarrow v v + jets$ (irreducible background)
- $-W \rightarrow I \nu + jets$ (with charged lepton lost)
- -Residual QCD and non-collision backgrounds.

Data driven prediction

CDF Run II Preliminary, 2fb-1

Background	125/80	225/100
Z → νν	777 ± 49	71 ± 12
$W \rightarrow \tau \nu$	669 ± 42	50 ± 8
$\mathbf{W} \rightarrow \mu \nu$	399 ± 25	33 ± 5
W → ev	256 ± 16	14 ± 2
Z → II	29 ± 4	2 ± 0
QCD	49 ± 30	9 ± 9
γ + jets	55 ± 13	5 ± 3
top	74 ± 9	11 ± 2
non-collision	4 ± 4	1 ± 1
Total	2312 ± 140	196 ± 29
Observed	2506	186



MET

100

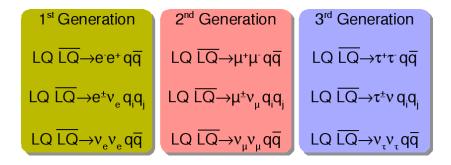
80

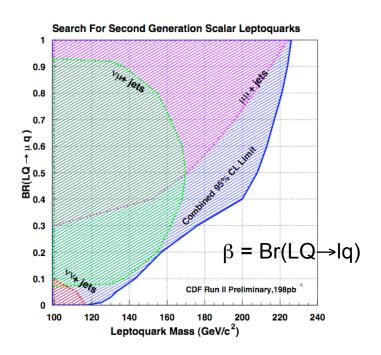
125

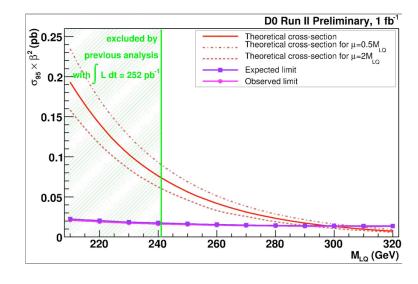
225

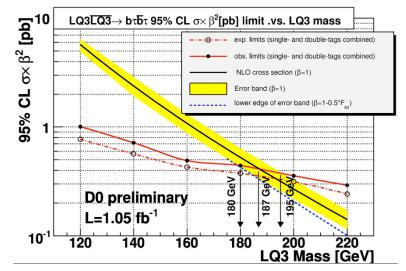
HT

Other Leptoquarks Results



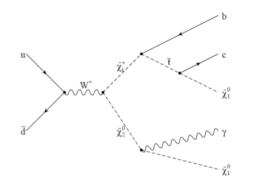






More complex signatures: γ+b+jets+MET^{Simona Rolli-Tufts University}

A handful of exotic processes would give rise to a final state signature comprising γ+b+jets+MET Many anomalies could be reduced to detector mis-measurements.



Low energy SUSY with radiative decay of the neutralino

Selection:

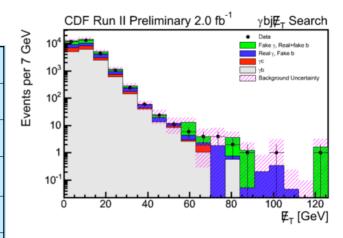
One high E_⊤ photon

≥ 2 jets

≥ 1 tagged jet Large MET (> 25 GeV) Topological cuts Main background is dominated by fake γ or b. Calculated using MC or data

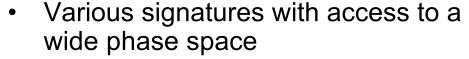
CDF Run II Preliminary, 2 fb⁻¹

Source	Number
γb	291 ± 7 (stat.) ± 50 (syst.)
γ c	92 ± 25 (stat.) ± 45 (syst.)
Fake b, real γ	141 ± 6 (stat.) ± 30 (syst.)
Fake γ	113 ± 49 (stat.) ± 54 (syst.)
Total	637 ± 54 (stat.) ± 128 (syst.)
Data	617

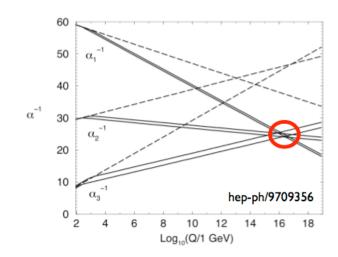


Search for Supersymmetry

- SUSY is a very popular extension of the SM…
 - It solves several open issues and provide and elegant description of bosons and fermions
- On the other hand...
 - Full set of new particles with constraints on their masses (TeV scale)



- Multileptons final states
- Jets and MET
- MET and γ
- Heavy flavors



Names	spin	R_P	Gauge eigenstates	Mass eigenstates
Higgs bosons	0	+1	$H_u^0 \; H_d^0 \; H_u^+ \; H_d^-$	$h^0 \; H^0 \; A^0 \; H^\pm$
			$ ilde{u}_L \; ilde{u}_R \; ilde{d}_L \; ilde{d}_R$	same
squarks	0	-1	\tilde{c}_L \tilde{c}_R \tilde{s}_L \tilde{s}_R	same
			$ ilde{t}_L \; ilde{t}_R \; ilde{b}_L \; ilde{b}_R$	$ ilde{t}_1 ilde{t}_2 ilde{b}_1 ilde{b}_2$
			$ ilde{e}_L \; ilde{e}_R \; ilde{ u}_e$	same
sleptons	0	-1	$ ilde{\mu}_L \; ilde{\mu}_R \; ilde{ u}_\mu$	same
			$ ilde{ au}_L ilde{ au}_R ilde{ u}_ au$	$ ilde{ au}_1 \; ilde{ au}_2 \; ilde{ u}_{ au}$
neutralinos	1/2	-1	$ ilde{B}^0 \ ilde{W}^0 \ ilde{H}_u^0 \ ilde{H}_d^0$	$\chi_1^0 \; \chi_2^0 \; \chi_3^0 \; \chi_4^0$
charginos	1/2	-1	$ ilde{W}^{\pm} ilde{H}_u^+ ilde{H}_d^-$	$\chi_1^{\pm} \; \chi_2^{\pm}$
gluino	1/2	-1	$ ilde{g}$	same
goldstino	1/2	-1	$ ilde{G}$	same

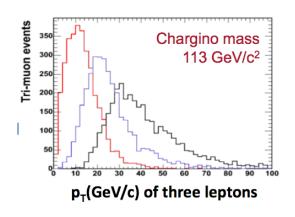
SUSY in Trileptons

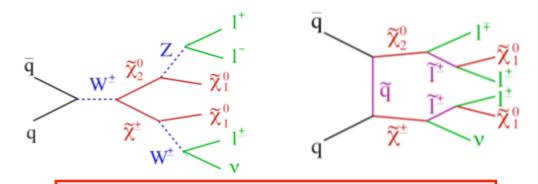
Very clean signature:

- 3 isolated leptons
- ullet u due to undetected $ilde{\chi}_1^0$ and u

Challenge:

- low cross section: $\sigma \times \mathcal{B}r < 0.5 \text{ pb}$
- very soft 3rd lepton p_T





Search Strategies

CDF: • 3 identified leptons (e, μ)

2.0 fb⁻¹ • 2 identified leptons + track (ℓ)

DØ: • 2 identified leptons (e, μ) + ℓ

2.3 fb⁻¹ • $\mu \tau + \ell$ and $\mu \tau + \tau$ (τ had decay)

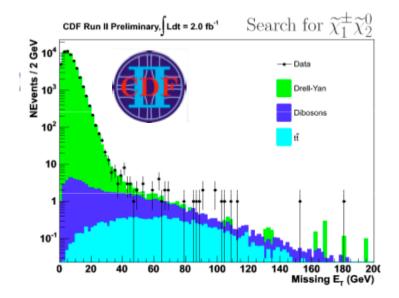
• "low"-pT vs "high"-pT search

Background is reduced with several set of kinematical cuts: inv-mass cut, lepton (track) p_T cut, ∉_T, M_T, ΔΦ between leptons, number of jets...

diboson (WW,WZ) Drell-Yan $W \to l
u, \, t \, ar t$

SUSY in Trileptons (cont'd)

 Signal region is investigated only after validating backgrounds in control regions (a blind analysis)



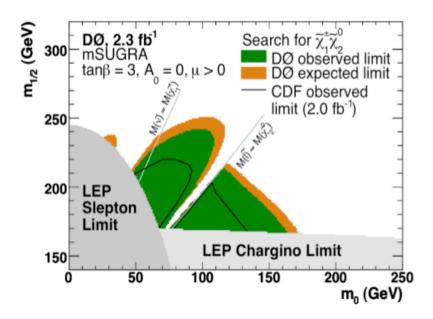
Control regions in MET vs Mee phase-space

 Signal region is investigated only after validating backgrounds in control regions (a blind analysis) Good agreement with SM background

$DØ \int \mathcal{L} dt = 2.3 \; \mathrm{fb}^{-1}$	CDF $\int \mathcal{L}dt = 2.0 \text{ fb}^{-1}$		
Background Data	Background Data		
low p _T 5.4±0.6 9	Trilepton 0.88±0.14 1		
high p_T 3.3 \pm 0.4 4	Lepton+track 5.5±1.1 6		

Data compatible with SM
Set limits in the mSUGRA model

Benchmark scenario: $A^0=0$, $\tan \beta=3$, $\mu>0$



 $e(p_3)$

Sneutrinos in $e+\mu/\tau$ final states

R-parity: $R_P = (-1)^{2S} (-1)^{3(B-L)}$

R-parity violation: automatic generation of neutrino masses and mixing... single sparticle can be produced

Very clean signature:

- 2 hard isolated leptons
- typical signal acceptance: 5 to 15%

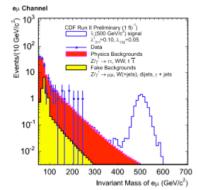
Search Strategies

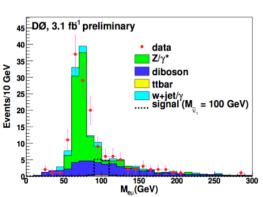
CDF: • 1.0 fb-1

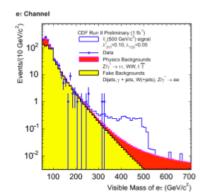
• 3 channels: eμ; μτ; eτ

DØ: • 4.1 fb-1

only one channel: eµ







 \tilde{v}

 $d(p_1)$

 $d(p_2)$

DØ places limits on λ'_{311} for several values of λ_{321} depending on the stau mass.

CDF places limits on the stau mass. Updated limits underway (using more accurate theo. predictions).

GMSB SUSY

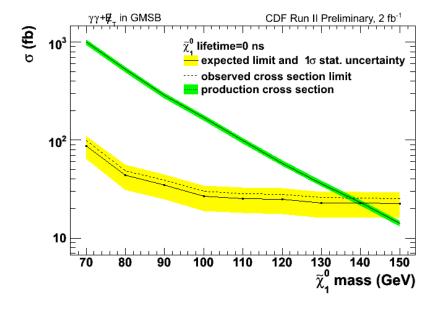
In gauge mediated SUSY breaking models, SUSY is broken in a hidden sector. The breaking is communicated to (s)quarks, (s)leptons and Higgs(ino) via gauge bosons and gaugino interactions.

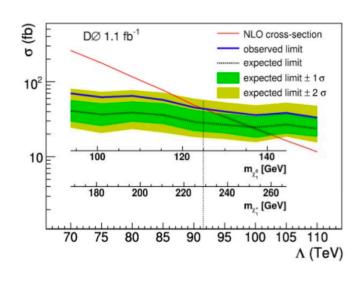
 $p\bar{p} \rightarrow (X \rightarrow) \chi^0_1 \chi^0_1$

Special features:

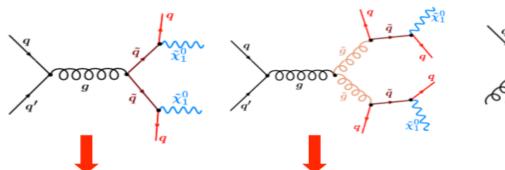
- gravitino is the LSP
- NLSP is a neutralino or a slepton
- NLSP can be fast enough to occur within the detector volume

- If NSLP = neutralino, one has:
$$\tilde{\chi}^0_1 \to \tilde{G} \gamma$$





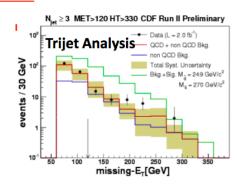
Squarks and gluinos: jets +MET



Result: 2 jets and MET Result: 4 jets and MET

Result: 3 jets and MET

- Although the production is strong, the analyses are challenging due to QCD-multijet and W/Z+jet backgrounds
 - **Solution**: break-down analyses in jet-multiplicity bins and optimize separately (using MET and HT←Sum of jet E_{τ})

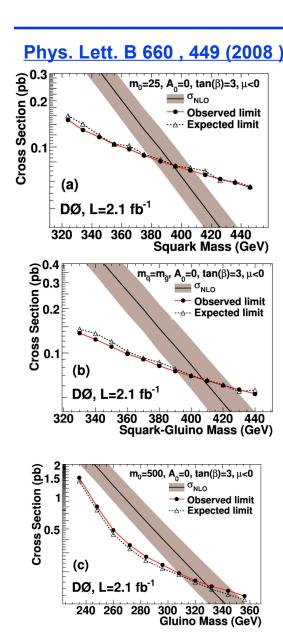


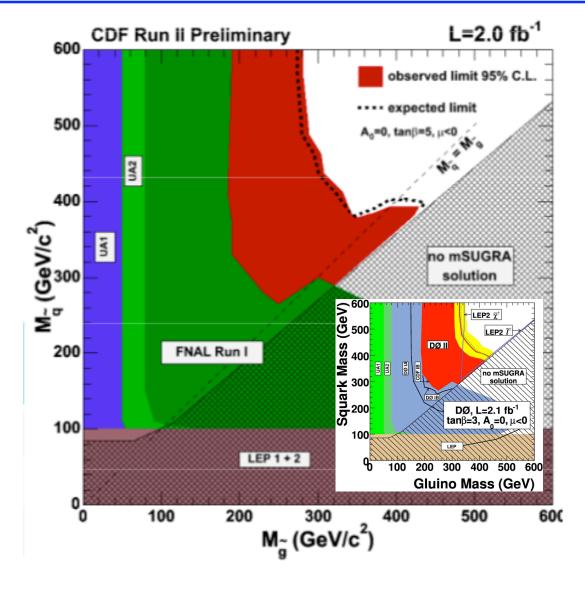
D0,PLB 660, 449 (2008), \mathcal{L} =2.1fb⁻¹

CDF Run II Preliminary, $\mathcal{L} = 2.0 \text{ fb}^{-1}$

Analysis	HT cut (GeV)	MET cut (GeV)	Jet Et (GeV)	Bckg.	DATA	Analysis	HT cut (GeV)	MET cut (GeV)	Jet Et (GeV)	Bckg.	DATA
Dijet	325	225	35,35	11 ± 1 +3/-2	11	Dijet	330	180	165,100	16 ± 5	18
Trijet	375	175	35,35,35	11 ± 1 +3/-2	9	Trijet	330	120	140,100,25	37± 12	38
4-jet	400	100	35,35,35,20	18 ± 1 +6/-3	20	4-jet	280	90	95,55,55,25	48 ± 17	45

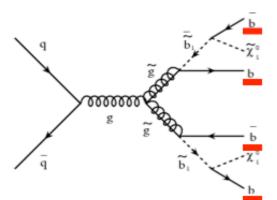
SUSY in MET + jets





Search for sbottom from gluino decay

If the sbottom is significantly lighter than the other squarks, the two body decay of gluino into bottom/sbottom is kinematically allowed



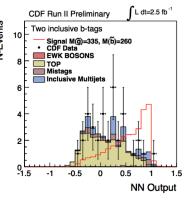
The sbottom decays into a bottom and LSP, giving rise to a final state with 4 b-jets and missing energy

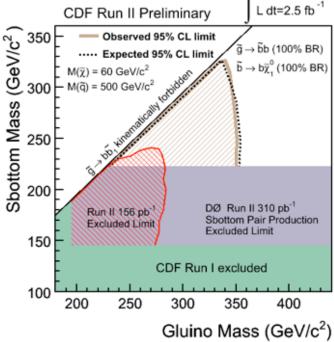
The analysis is optimized for 2 points in the SUSY parameter space:

Large Δm between \tilde{g} and \tilde{b} $M(\tilde{g}) = 320 \; \text{GeV/c}^2, \; M(\tilde{b}) = 250 \; \text{GeV/c}^2, \; M(\tilde{\chi}) = 60 \; \text{GeV/c}^2$ Small Δm between \tilde{g} and \tilde{b}

 $M(\tilde{g}) = 300 \text{ GeV/c}^2$, $M(\tilde{b}) = 280 \text{ GeV/c}^2$, $M(\tilde{\chi}) = 60 \text{ GeV/c}^2$

In the signal region a further optimization is performed using a neural network output



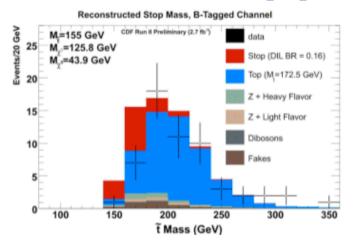


Stop Searches

If stop light enough, $m[\tilde{t}] < m[t]$, several interesting decays, depending on the sparticles spectrum:

I. CDF 2.7 fb⁻¹: dileptons (e/ μ) with one isolated lepton, \not{E}_T , high p_T jets, b-tagging. reconstruct the stop mass with a kinematic fit.

$$\tilde{t}_1\bar{\tilde{t}}_1 \rightarrow b\,b\,l\,l'\,\nu\,\overline{\nu}\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$



I.
$$\tilde{t} \rightarrow b \, \tilde{\chi}_1^+ \rightarrow b \, l \, \nu \tilde{\chi}_1^0 \quad (m_{\tilde{\chi}_1^+} < m_{\tilde{t}})$$

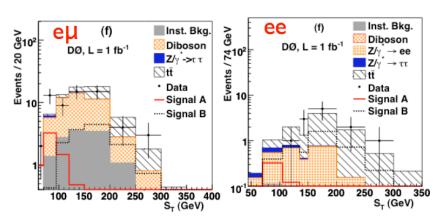
2.
$$\tilde{t} \rightarrow b \, \tilde{\nu} \, l$$
 $(m_{\tilde{\chi}_1^+} > m_{\tilde{t}})$

3.
$$\tilde{t} \rightarrow c \, \tilde{\chi}_1^0$$

2. **D**Ø **I.0 fb**⁻¹: ee, eμ.

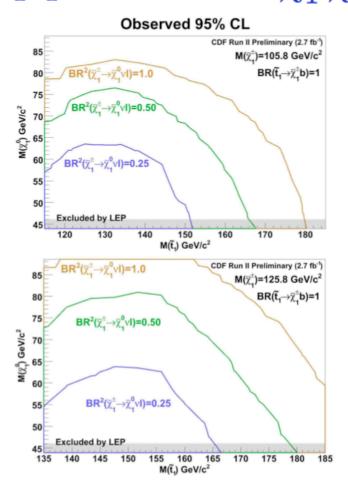
Signal efficiency ranges from 0.1 to 10% depending on $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\nu}}$

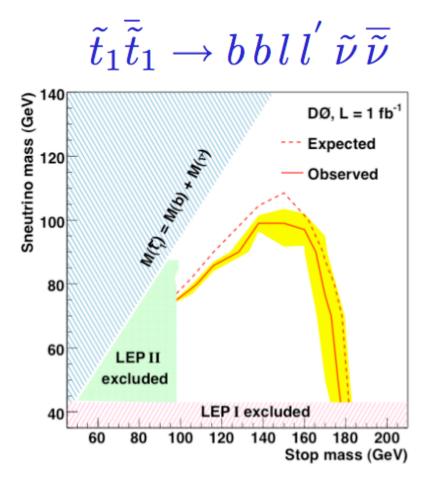
$$\tilde{t}_1 \overline{\tilde{t}}_1 o b \, b \, l \, l^{'} \, \tilde{\nu} \, \overline{\tilde{\nu}}$$



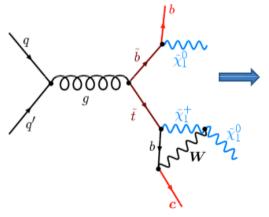
Stop Searches (cont'd)

$\tilde{t}_1\bar{\tilde{t}}_1 \rightarrow b\,b\,l\,l'\,\nu\,\overline{\nu}\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$





Stop searches (cont'd)



Stops to charm

$$\tilde{t} \rightarrow c \, \tilde{\chi}_1^0$$

- Exactly 2 jets (reduction of QCD)
- Jet pt cuts (20,40 GeV/c) and angular separation of jets (reduces QCD and W+jets)
- Angle between jets and met (reduction of QCD)
- Flavor tagging using Neural Network (impact parameter, secondary vertex information)

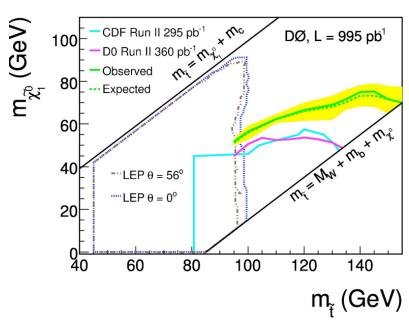
Exclusion: stop mass <149 GeV/c² for neutralino mass of 63 GeV/c²

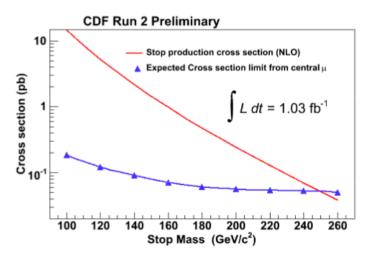
Other option is that stop does not decay in the detector (CHAMP)

- Slow particle signature: slowly-moving highly-ionizing highly-penetrating particle
 - Will look like muon with possible calorimetry energy deposition
 - Particle mass is measured using Time of Flight

Stable stop mass > 250 GeV/c² at 95% CL

Fermilab-PUB-08/063-E







Many exciting results are continuously produced at the Tevatron!

The search for physics beyond the SM is carried on through a careful analysis of various final states using model driven as well as signature based approaches.

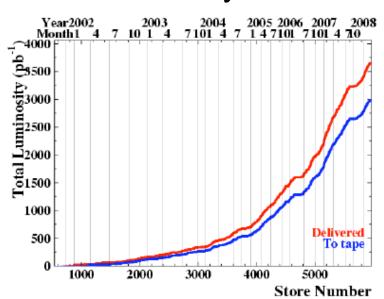
A bump can be around the corner before the LHC turns on....

Backup

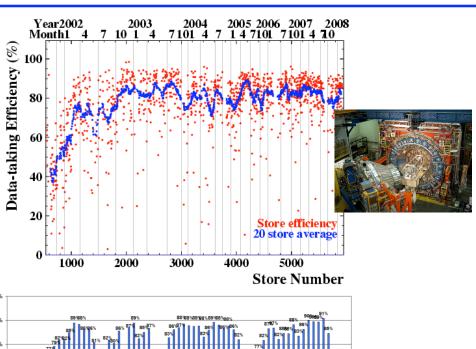
TeVatron Status

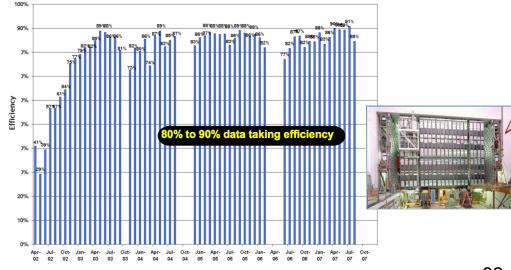
The TeVatron is doing very well!

Luminosity Profile



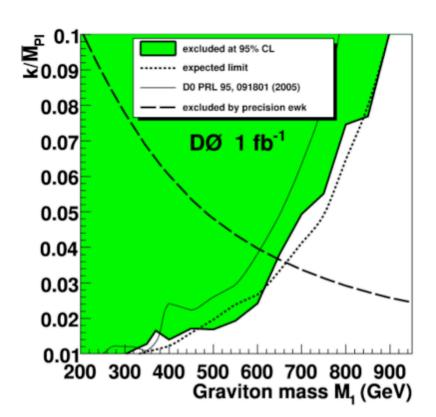
Delivered Lumi. > 3.6 fb⁻¹ Good for analysis ~ 3. fb⁻¹

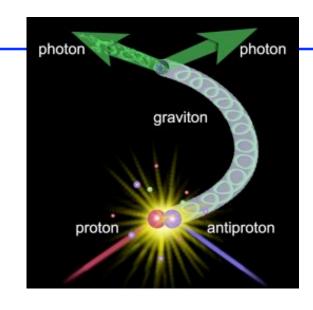


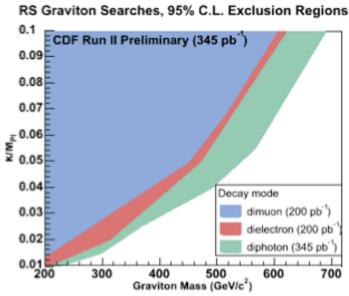


Diphotons final state:LED

The search for new particles decaying to diphotons uses the RS graviton model to express sensitivity to Kaluza-Klein graviton resonances (spin 2 resonance)







Jets and Heavy Flavor

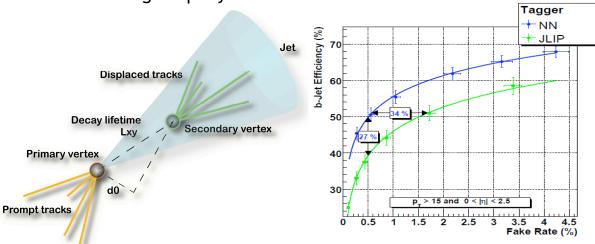
Hadronic jets are reconstructed using several algorithms: Cone, Midpoint, KT etc..

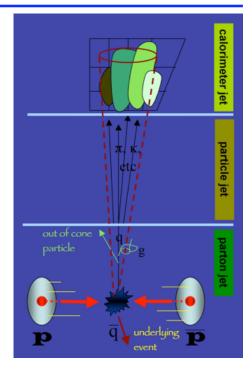
Measured jet energies are corrected to scale them back to the final state particle level jet . Additionally there are corrections to associate the measured jet energy to the parent parton energy, so that direct comparison to the theory can be made. Currently the jet energy scale is the major source of uncertainty in the measurement of the top quark mass and inclusive jet cross section

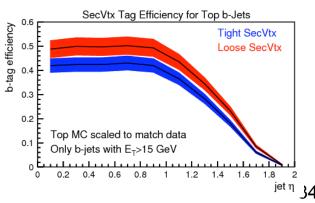
B-jet identification is implemented via:

- -displaced vertices with L_{xy}/σ cut (CDF)
- -Vertex mass separation (CDF)
- -combining vertex properties and displaced track info with NN (D0)





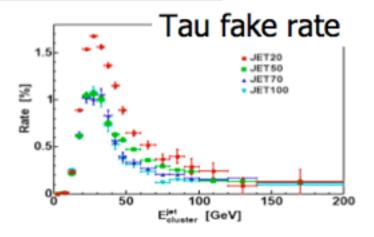




Lepton Efficiencies

 Compare "typical" high-pt (>20 GeV) isolated lepton efficiency and fake rates

Lepton	Efficiency	Fake Rate
electron	~80%	~0.01%
muon	~85%	~0.01%
tau (box cuts)	~45%	~1-0.1%
tau (neural net)	~80%	~5-1%



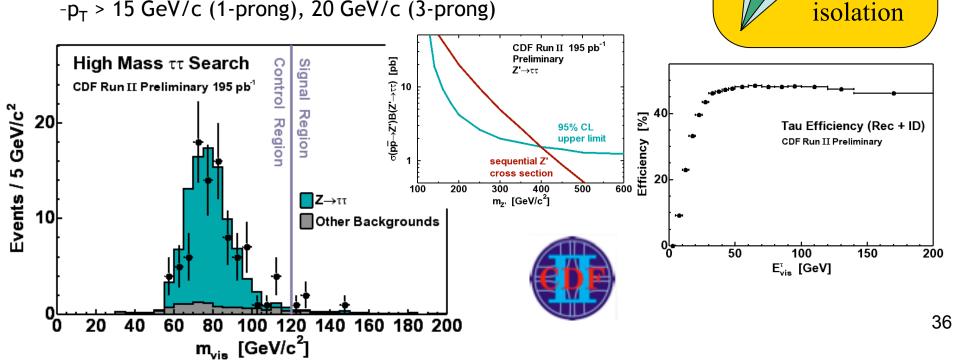
τcone

 $\tau_h ID$

Taus final states

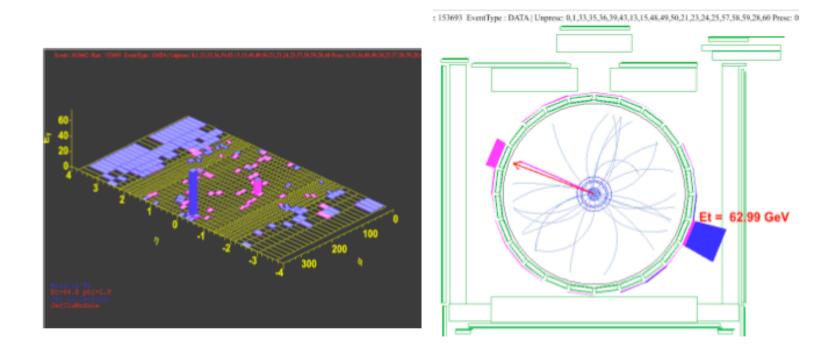
Ditaus final states are selected where

- •One tau decays leptonically: e/μ (CDF) μ (DØ) (plus v's)
- • $p_T > 10 \text{ GeV/c (CDF)}, p_T > 15 \text{ GeV/c (DØ)}$
- -Other tau hadronic (and v_{τ})
 - -One or three tracks ($\Sigma q_{trk} = \pm 1$), opposite to lepton
 - -CDF: isolation 30°, shrinking τ cone (10° \rightarrow 3°)
 - -DØ: three types (π^{\pm} , $\pi^{\pm}\pi^{0}$, 3-prong), NN score
 - •No electron veto (allows eμ)
 - $-p_{T} > 15 \text{ GeV/c (1-prong)}, 20 \text{ GeV/c (3-prong)}$



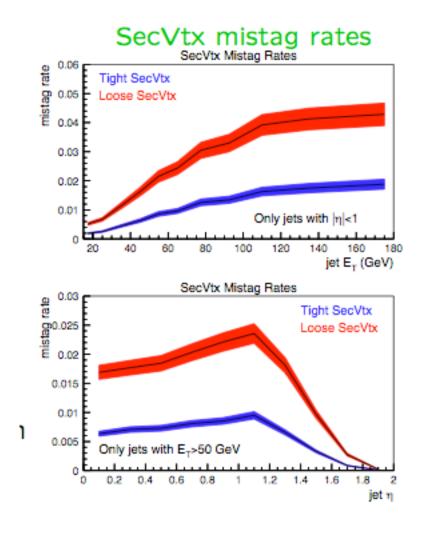
Z Tau event

Simona Rolli - Tufts University

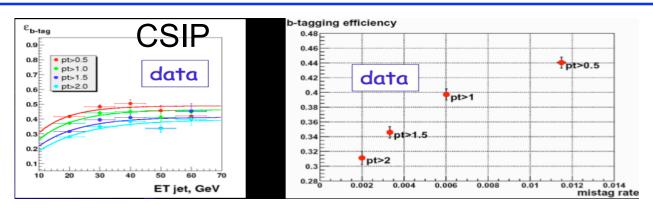


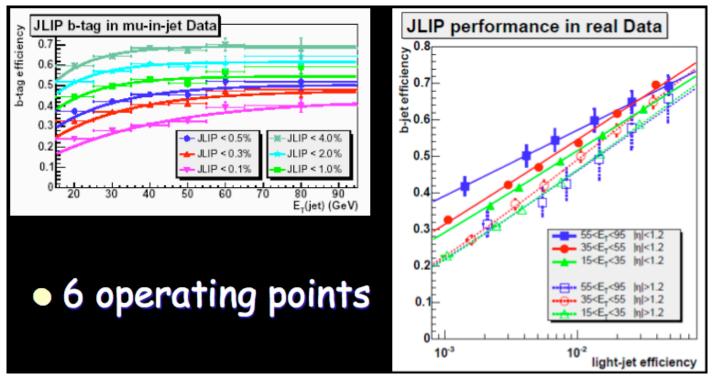
Mass (
$$\tau_e + \tau_h + MET$$
) = 129 GeV/c²

Btagging Mistag Rate



D0 btagging





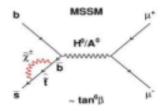
SUSY current status

Sparticle	Low mass limit (GeV/c²)
Chargino (mSUGRA)	~140-150
NL Neutralino (mSUGRA)	~140-150
Chargino (GMSB)	~230
LSP Neutralino (GMSB)	~125
Chargino mSUGRA, RPV	~200
Neutralino mSUGRA, RPV	~100
Squark	~400
Gluino	~300
Light stop or RPV stop	~150
Stop as CHAMP	~250

http://www-d0.fnal.gov/Run2Physics/WWW/results/np.htm http://www-cdf.fnal.gov/physics/exotic/exotic.html

$B_s \rightarrow \mu\mu$

Sensitive to new physics: if no observation, it can strongly constraint SUSY models



SM prediction: $BR = 3.42 \times 10^{-9}$ SUSY enhancement ~(tanβ)6

- Extract signal with Neural Net based discrimina and Bd considered separately:

B_c and B_d considered separately:

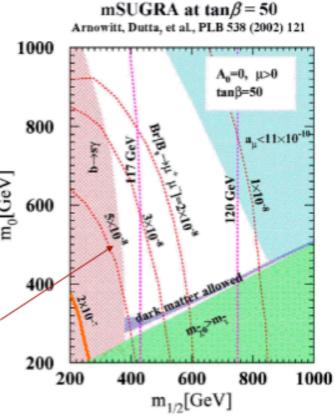
Bs→µµ 3 observed events (3.6+/-0.3 exp.bkg.)

Bd→μμ 6 observed events (4.3+/-0.3 exp.bkg.)

No significant excess → exclusion limit

Br(B_s
$$\rightarrow$$
μμ)<5.8×10-8 @ 95% CL
Br(B_d \rightarrow μμ)<1.8×10-8 @ 95%CL

Comb CDF/D0



BR($B_c \rightarrow \mu\mu$) < 1.5x10-7 @95% CL

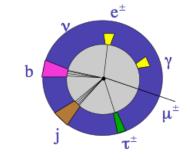
hep-ex/0508058

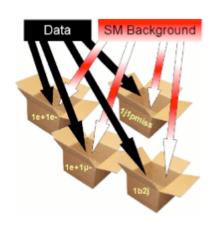
Global Searches

The goal is to perform a model-independent global search of high P_T data:

- -study bulk features of high P_⊤ data;
- -search for resonances invariant mass distributions
- -search for significant excesses at high sum-p_T

Physics objects are categorized and events selected and partitioned into ~400 exclusive final states





The whole high P_T region is monitored at once

Pythia and MadEvent are used to implement the SM theoretical prediction (CdfSim emulates the detector response)

Many correction factors are used to obtain the *true* SM predictions (shouldn't a global search work globally?)

theory k-factors etc experimental efficiencies and Scale Factors, fake rates etc

Currently observed discrepancies are explained in terms of incorrect MC modeling